MEASUREMENT AND CORRECTION OF LINEAR OPTICS AND COUPLING AT TEVATRON COMPLEX[♦]

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Introduction

Tevatron luminosity has been affected by optics imperfections.

Two major problems have been encountered:

- ~15% emittance growth at injection due to strong X-Y coupling
- Optics mismatches at collisions caused ~30% increase of beta-functions in IPs with corresponding luminosity loss of ~15-20%

Optics measurements and correction have been complicated by

- Poor performance of 30 years old BPM system
  - Poor BPM accuracy, ~150 μm rms resolution
  - Not functional ring wide turn-by-turn mode of BPM operation
- Limited time for optics measurements and studies

Now the only reliable way for optics measurements is the differential optics measurements, i.e. the orbit response to a single correct. bump

- Fast measurements have been used during last two years
  - Only four correctors and energy change are exercised
- Presently, we introduce the extended measurements where about half of available correctors are used and SVD is applied for data analysis

Emittance Growth due to X-Y coupling at Injection

Tevatron dipoles have coherent skew-quadrupole component

- It has been developed due to compression of thermo-insolating coil support with corresponding settling SC coil relative to the iron core
  - Coil displacement: ~150 μm down relative to the core
  - Skew quad gradient: GA/B_0~(1.5-2) 10^{-4} for A=2.54 cm
- While the value does not look large it causes very strong coupling
  - Uncompensated tune split $\Delta Q \sim 0.2$

Compensation of the tune split is used for coupling suppression

- It has been insufficient to suppress the emittance growth at injection

Most of dipoles have nearby skew-quadrupole corrector and their effect is well compensated. But after the collision optics has been installed in eighties 112 of 774 dipoles lost nearby skew-quad, which significantly worsened the coupling correction

- During summer 2003 shutdown the skew-quadrupole component for these 112 dipoles was corrected.
- That significantly reduced effects of the coupling on emittance growth

Calculations of the emittance growth due to coupling at injection

- For coupled motion the eigen-vectors can be parameterized as

$$\mathbf{v}_1 = \begin{bmatrix} \sqrt{b_{1x}} \\ -\dfrac{i(1-u)+a_{1x}}{\sqrt{b_{1x}}} \\ \sqrt{b_{1y}}e^{in_1} \\ -\dfrac{iu+a_{1y}}{\sqrt{b_{1y}}}e^{in_1} \end{bmatrix}, \qquad \mathbf{v}_2 = \begin{bmatrix} \sqrt{b_{2x}}e^{in_2} \\ -\dfrac{iu+a_{2x}}{\sqrt{b_{2x}}}e^{in_2} \\ \sqrt{b_{2y}} \\ -\dfrac{i(1-u)+a_{2y}}{\sqrt{b_{2y}}} \end{bmatrix}$$

  where $b_{nx,ny}$ and $a_{nx,ny}$ are the beta- and alpha-functions, and parameters u, n_1 and n_2 are determined by the symplecticity conditions.

- The particle motion can be written in the following form

$$\mathbf{x} = \frac{1}{2}\left(\sqrt{2e_1}\,\mathbf{v}_1 e^{im_1} + \sqrt{2e_2}\,\mathbf{v}_2 e^{im_2}\right) + c.c$$

  where e_1 and e_2 are the rms single particle emittances, and m_1 and m_2 are the betatron phase advances. The emittances can be computed from the particle coordinates using following equation

$$e_1 = \frac{1}{2}\left(\mathbf{v}_1^{+}\mathbf{U}\mathbf{x}\right)^2, \quad e_2 = \frac{1}{2}\left(\mathbf{v}_2^{+}\mathbf{U}\mathbf{x}\right)^2$$

  where $\mathbf{U}$ is the symplectic unit matrix, $\mathbf{U} = \begin{bmatrix} 0 & \mathbf{u} \\ \mathbf{u} & 0 \end{bmatrix}, \mathbf{u} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$

- Initial distribution function for the injected beam can be written as

$$f(\mathbf{x}) = \frac{1}{4p^2 e_1 e_2} \exp\left(-\frac{1}{2} \mathbf{x}^T \mathbf{?}\, \mathbf{x} \right)$$

where matrix X is determined by the eigen-vectors, $\mathbf{v}_{t1}$ and $\mathbf{v}_{t2}$ of the incoming beam

$$\mathbf{?} = \mathbf{U}\mathbf{V}_t \mathbf{?}' \mathbf{V}_t^T \mathbf{U}, \quad \mathbf{?}' = \begin{bmatrix} e_1^{-1}\mathbf{I} & 0 \\ 0 & e_2^{-1}\mathbf{I} \end{bmatrix}, \quad \mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{V}_t = [\operatorname{Re}\mathbf{v}_{t1}, \ -\operatorname{Im}\mathbf{v}_{t1}, \ \operatorname{Re}\mathbf{v}_{t2}, \ -\operatorname{Im}\mathbf{v}_{t2}]$$

- Then the emittance of the injected beam relative to the ring lattice is

$$e_i' = \frac{1}{8p^2 e_1 e_2} \int dx^4 \left(\mathbf{v}_i^{+} \mathbf{U}\mathbf{x} \right)^2 \exp\left(-\frac{1}{2} \mathbf{x}^T \mathbf{?}\, \mathbf{x} \right)$$

- For initially uncoupled beam characterized by b_x, a_x, b_y and a_y that yields

$$e_1' = e_1 A_{11} + e_2 A_{12}$$

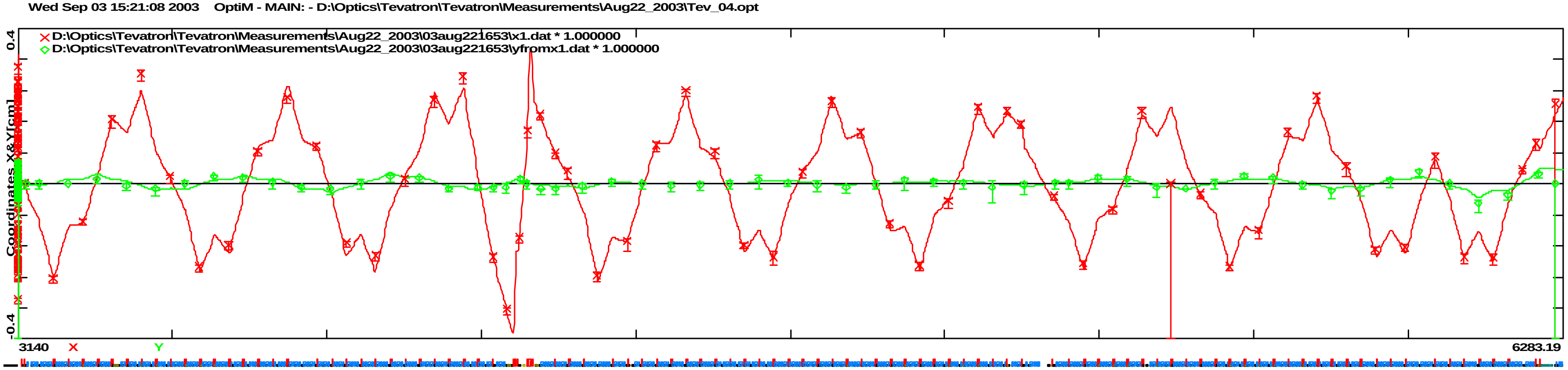
$$e_2' = e_1 A_{21} + e_2 A_{22}$$

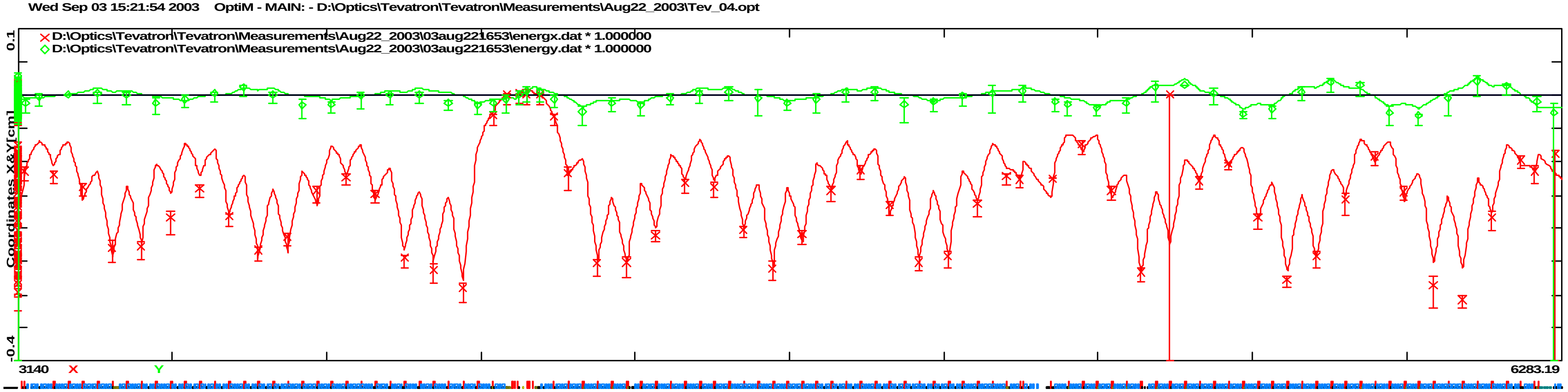
$$A_{11} = \frac{1}{2}\left(\frac{b_x}{b_{1x}} \left[(1-u)^2 + a_{1x}^2 \right] + \frac{b_{1x}}{b_x} \left[1 + a_x^2 \right] - 2a_{1x} a_x \right), \quad A_{12} = \frac{1}{2}\left(\frac{b_y}{b_{1y}} \left[u^2 + a_{1y}^2 \right] + \frac{b_{1y}}{b_y} \left[1 + a_y^2 \right] - 2a_{1y} a_y \right),$$

$$A_{21} = \frac{1}{2}\left(\frac{b_x}{b_{2x}} \left[u^2 + a_{2x}^2 \right] + \frac{b_{2x}}{b_x} \left[1 + a_x^2 \right] - 2a_{2x} a_x \right), \quad A_{22} = \frac{1}{2}\left(\frac{b_y}{b_{2y}} \left[(1-u)^2 + a_{2y}^2 \right] + \frac{b_{2y}}{b_y} \left[1 + a_y^2 \right] - 2a_{2y} a_y \right)$$

Results of optics measurements and correction

Differential orbit measurement results at injection





C0 D0 E0 F0

Measured data (crosses) and the Tevatron model predictions (lines) for differential orbits excited by one of horizontal correctors and by the energy change; red lines – horiz. plane; green lines – vert. plane, only half of the Tevatron length is presented

Analysis of diff. orbit data at injection exhibited the following

- There is systematic difference between main bus SC dipoles and quads
  - Comparing to magnetic meas. (~30 years old) quads are ~0.15% stronger
- Systematic skew-quad field in dipoles is $G_s A/B_0 \sim 1.4 \cdot 10^{-4}$ for A=2.54 cm
  - It is in good agreement with measured displacement of coils ~150 μm
- There are significant non-systematic (point-like) focusing and skew-focusing errors scattered through the entire machine
  - To fit the data we have applied ~30 quad and/or skew-quad corrections with strengths [0.5 – 2%] of the main bus quad strength

Twiss parameters for proton and pbar injection computed from the model

	Central orbit, proton injection point		P-bar helix, pbar injection point	
	Mode 1(X)	Mode 2 (Y)	Mode 1 (X)	Mode 2 (Y)
b_x	9989.06	1641.6	7723.07	957.12
a_x	-0.8255	-0.199957	-0.652	-0.146
b_y	1066.5	5660.5	720.2	6491.6
a_y	0.0378	0.1604	-0.0608	0.5681
ν	-110.96^0	-90.8^0	-0.22^0	-0.38^0
u	-0.0276832		.0149636	

The model has been used to compute 4D Twiss parameters at injection point.

- It yielded ~15% emittance growth related to coupling
- The model predicted that after correction of skew-fields in 112 dipoles (which do not have near-by skew-quad) the emittance growth has to be decreased to ~3-5%
  - That was verified by the luminosity increase after summer 2003 shutdown

Optics correction at injection (150 GeV)

- To verify an accuracy of the model we compared measured and computed tune shifts due to quad current changes
  - Comparatively large discrepancy (up to 15%) is related to the fact that Tevatron tunes (Qx=20.585, Qy=20.575) are quite close to half integer resonance. That additionally amplifies effects of optics errors on the beta-functions
- Differential orbit measurements exhibited sufficiently small optics imperfections
  - Therefore on-line optics measurements were based on measurements of tune shifts due to strength changes of one of 4 designated quads. "Resonant" optics correction was performed with 4 other quads.

Optics measurements and correction at low beta (980 GeV)

- Similar to the injection energy we performed optics measurements at low beta, where errors of focusing in the interaction region quads dominate errors in the sectors. The following conclusions were drawn out
  - There is systematic difference between main bus SC dipoles and quads

- Comparing to magnetic meas. quads are ~0.18% stronger. That is consistent with measurements at injection energy
- Systematic skew-quad field in dipoles is $G_s A/B_0 \sim 2.1 \cdot 10^{-4}$ for A=2.54 cm
  - It is about 40% higher than at injection energy. Origin is unknown.
- There are significant non-systematic (point-like) focusing and skew-focusing errors scattered through the entire machine
  - While relative values and number of corrections are similar to the injection energy but their distribution along the ring is different
- Interaction region quads
  - Need to be fudged up to 1% as a power supply family. It is well above one would expect
  - Additionally, there is about 0.1% difference for quads of the same design
- Model exhibited that due to optics mismatches the beta-functions in IPs were ~30% above design value and there was significant betatron function mismatch through entire machine

♦ First step of optics correction was carried out to correct optics mismatches in IPs. There is still considerable mismatch in arcs. We plan to perform next step before September 2004

Extended differential orbit measurements

- The data analysis of differential orbit data, additionally to optics errors, is complicated by difference in BPM response for different BPMs, their rolls, as well as by rolls of correctors and errors in their strength
- To take this into account we have used a method proposed in Ref. [1]. The effort is build as collaboration between FNAL and ANL and aimed to upgrade the software developed for APS [2]. The major requirements are its integration with FNAL data structures and optics software and the requirement to take into account X-Y coupling and both dispersions
  - We put as unknown: Quad strengths and rolls, BPM responses and rolls, correctors strength and rolls – altogether about 800 unknowns
  - To have sufficient redundancy with perform measurements with 50 correctors which yields ~10,000 equations
  - SVD is used to find unknowns from the measured data
- The first results of data analyses have been recently obtained. Further work is required to finish the project.

Response matrix fit (non-coupled case) at Low Beta optics

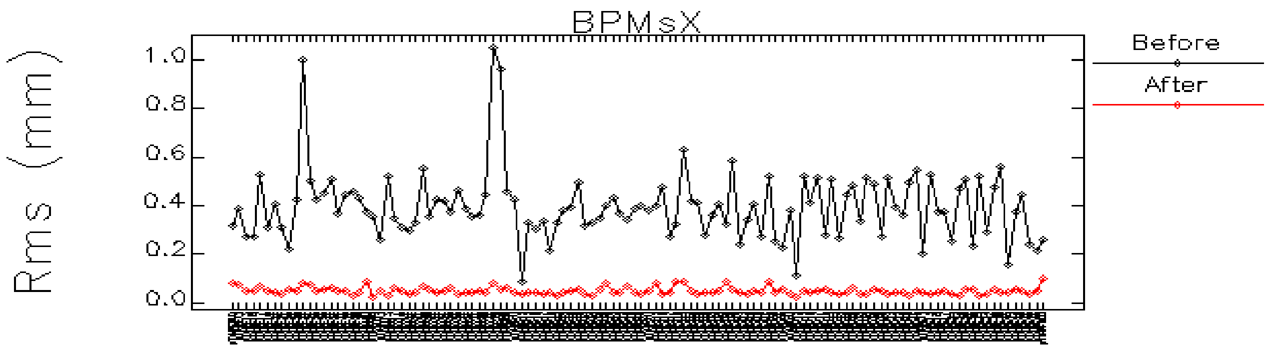
Number of variables: 503

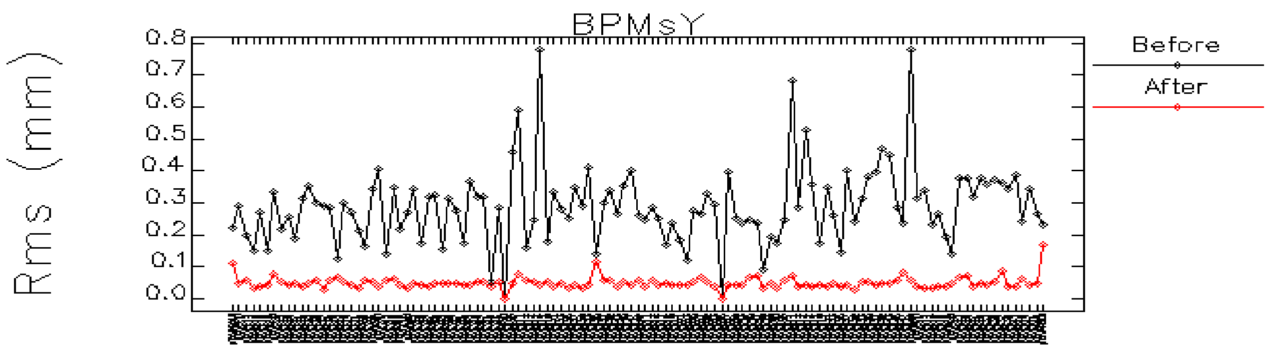
Number of measurements (equations): 6291

Rms difference between measured and calculated response matrix:

Before the fit: 370 μm

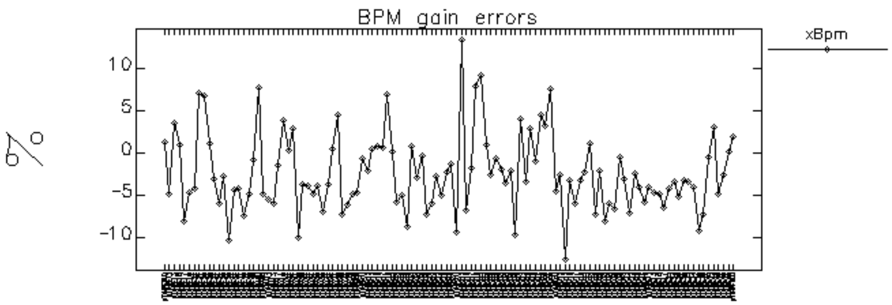
After the fit: 50 μm

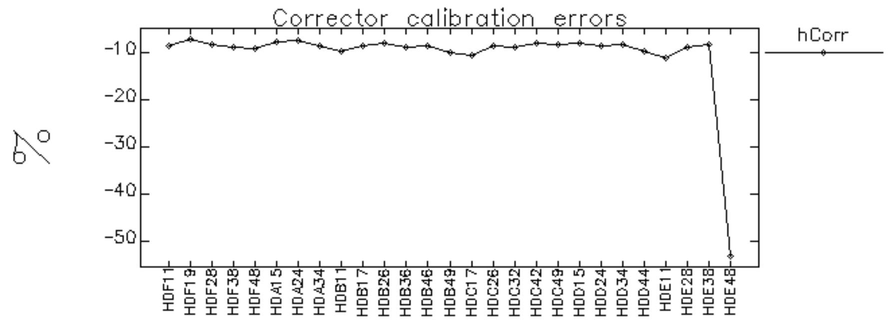


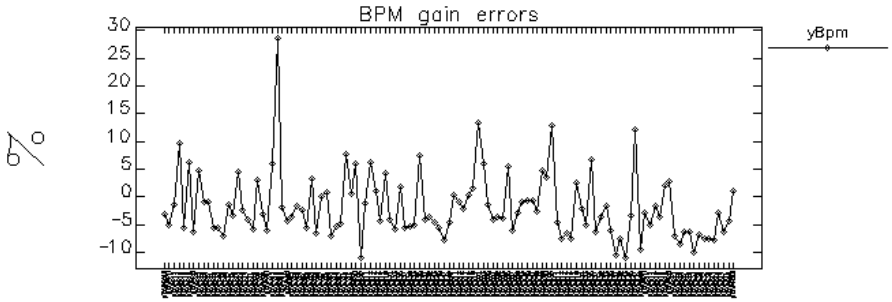


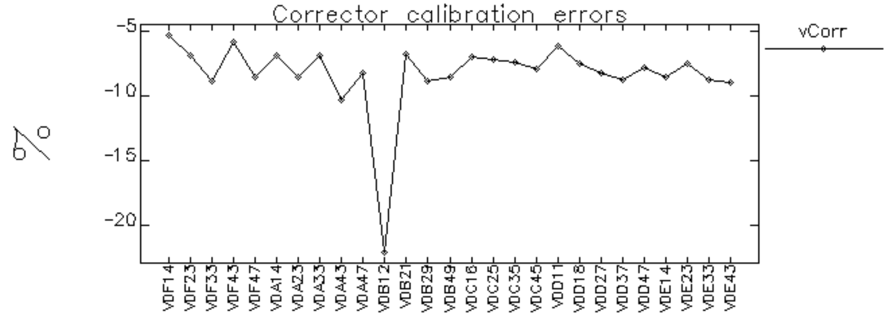
Rms difference for each BPM before and after the fit:

BPM and corrector errors:









Conclusions

- We build a model of Tevatron optics
  - It is based on (1) the differential orbit measurements and (2) the limited number of beta-function measurements in quads obtained by tune changes due to quad strength change
  - The model includes actual power supply currents
  - The results of magnetic measurements were fudged to match the model predictions and the measurements
- The model has been used to correct Tevatron optics and X-Y coupling. That allowed us
  - To decrease the emittance growth due to optics mismatch and coupling at injection (~10-15%)
  - To decrease beta-functions in IPs from ~45 cm to the design values of 35 cm

  These optics corrections contributed into collider luminosity growth of ~20-30%

- Presently, the accuracy of the model is limited by poor accuracy of BPM data and inefficient data processing. We are carrying out the following actions to improve accuracy of the model
  - Upgrade of BPM electronics will boost BPM accuracy from ~150 μm to 20 μm rms and will allow to acquire turn-by-turn data for all BPMs
  - Improvements in data analysis will make data processing faster and more accurate
  - Using turn by-turn data will further improve accuracy of the measurements and will allow to measure non-linearities of the lattice

References

1. W. J. Corbett, M. Lee and V. Ziemann, PAC"93, Washington, DC, p. 108, 1993.
2. V. Sajaev, L. Emery, EPAC"02, Paris, France, p. 742, 2002.